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A STRESS-STRAIN-TIME MODEL (SST) FOR HIGH-TEMPERATURE, LOW-CYCLE FATIGUE

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A Stress-Strain-Time Model (SST) has been developed to predict high-temperature, low-cycle fatigue life. The model states that the life can be predicted by three variables--stress, strain, and time. These three variables are combined in a power-law equation to predict the life. The stress parameter accounts for mean stress effects. The strain parameter accounts for time-independent fatigue damage, and the time parameter accounts for the time dependence of fatigue life. High-temperature, low-cycle fatigue data for several alloy

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20. Abstract Continued

systems are correlated to within a factor of 2.1, and data are predicted to within a factor of 2.6 using the SST Model.

FOREWORD

This report was prepared by the Research Applications Division, Systems Research Laboratories, Inc., Dayton, OH, under Contract No. F33615-76-C-5191, "Mechanical Property Testing and Materials Evaluation." The contract was initiated under Project No. 7351, Task No. 735106, and was administered under the direction of the Air Force Materials Laboratory, Metals Behavior Branch (AFML/LLN), by Dr. Theodore Nicholas, Project Manager. The research reported here was conducted by H. L. Bernstein and was performed during the period January 1978 to August 1978.

The author gratefully acknowledges valuable discussions with Dr. N. Ashbaugh of Systems Research Laboratories, Inc., Dr. D. Stouffer of the University of Cincinnati, Dr. A. Chakrabarti of Detroit Diesel Allison, and the personnel of the Metals Behavior Branch of the Air Force Materials Laboratory (AFML/LLN). He also wishes to thank Mrs. J. Gandhi, Ms. M. Whitaker, and Ms. J. Paine for preparation of the manuscript. This research was performed under Air Force Contract F33615-76-C-5191.

LIST OF ILLUSTRATIONS

LIST OF TABLES

TABLE OF CONTENTS

INTRODUCTION

Low-Cycle Fatigue (LCF) at high temperature is a failure mode that is receiving a great deal of attention. It is a problem in fuel cladding and pressure-vessel design for nuclear reactors and in hot-section components for jet engines, as well as for other applications. High-temperature LCF is a particularly difficult problem because environmental attack and creep deformation interact with the basic fatigue mechanisms. The nature of this interaction is not understood, and much debate has occurred over whether the problem is mainly one of environment or creep interacting with fatigue.

Many models to predict high-temperature LCF have been proposed with varying success. The most prominent of these models are the Strainrange-Partitioning Model of Manson, Hirshberg and Halford,[1,2,3] the Frequency-Separation Model of Coffin,[4,5] the model of Ostergren,[6,7] and the Damage-Rate Model of Majumdar and Maiya.[8,9,10] Each of these models takes a different approach to high-temperature LCF. The Strainrange-Partitioning Model considers the problem to be one of creep interacting with fatigue, while the Frequency-Separation Model deals mainly with environment interacting with fatigue. The Ostergren Model attempts to incorporate mean stress effects and accounts for the various time dependencies by using different frequency terms. The Damage-Rate Model postulates a crack and cavity-growth law which is integrated over the loading cycle to give the fatigue life. The model considers the inelastic strain rate to be an important variable in addition to the inelastic strainrange.

Each of these four models was evaluated for its ability to predict the fatigue life of René 95 at 1200°F (650°C).* It was found that none of these models could correlate or predict the data to within a factor of two. The best results were obtained with the Ostergren Model, which correlated the data to within a factor of 3.6 and predicted it to within a factor of 5.2.[11]

Since none of these four models could predict the René 95 data to within a factor of two, another model was developed. The initial model was formulated for René 95 by making various modifications to the Ostergren Model. The modification that gave the best results was obtained by separating the cross-product term of the inelastic strainrange and the tensile stress into two separate terms.

Having successfully used this model for René 95, attempts were made to apply the model to data for other materials. It was found that this first version of the model was unable to correlate data for most of the materials to within a factor of two. Consequently, further adjustments were made to improve the model for all the materials considered. Since all the modifications were of a similar nature, they fit into a general framework which eventually became the present version of the model. This present version is called the Stress-Strain-Time Model (SST).

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*René 95 is an advanced Ni-base superalloy used for jet-engine turbine disks. This particular René 95 was a cast and wrought, thermo-mechanically processed product.

DESCRIPTION OF THE MODEL

The SST Model is an empirical model which is physically reasonable. The model combines those factors which are known to influence the high-temperature LCF life into a power-law equation. Different factors may be used, depending upon the material and temperature. Thus, the model provides a framework into which different material behavior can be incorporated.

Such a model is physically reasonable because the fatigue mechanisms at elevated temperature are a function of both the material and test temperature. For example, depending upon the temperature, certain materials are affected more by environmental attack than by creep strains; other materials behave in the opposite manner. Therefore, the variables used to predict the life would be expected to depend upon the particular material and test temperature. That is, the fatigue mechanisms for a given material at a given temperature determine the variables needed to predict the life.

At room temperature the LCF life is primarily a function of the strainrange -- either inelastic, elastic or total strainrange. When mean stresses are present, they affect the life and must be taken into account. At high temperature a time dependency is introduced into the LCF life. The exact nature of this time dependency is not known. The high-temperature LCF life is thus a function of three basic variables: (i) a measure of the strainrange, $\Delta\varepsilon$; (ii) a measure of the mean stress, σ; and (iii) a measure of the time in a cycle, τ. The SST Model postulates a power-law equation composed of these three basic variables in order to predict the life, N_f

$$N_f = A\left(\frac{\Delta\varepsilon}{\varepsilon_f}\right)^b \left(\frac{\sigma}{\sigma_y}\right)^c \tau^d \qquad (1)$$

where A, b, c, and d are material constants. The strainrange and stress terms are normalized by the true strain at fracture, ε_f, and the yield stress, σ_y.

The specific choice of variables for the stress, strain, and time terms depends upon the particular material and test temperature. At present, three variables have been investigated for the strain term, two for the stress term, and three for the time term.

The variables for the strain term are the elastic, inelastic, and total strainranges. The inelastic strainrange, $\Delta\varepsilon_{inel}$, and the elastic strainrange,* $\Delta\varepsilon_{elas}$, are used because they are basic measures of time-independent fatigue damage. The total strainrange is used because for some materials it provides a more linear relationship with the life.[12]

The variable used for the stress term is the peak tensile stress, σ_t. The peak tensile stress has correlated the data very well for René 95 at 1200°F (650°C), and it has been used by Walker[13] and Rice, <u>et al</u>.,[14] to account for mean stress effects at room temperature. A difficulty occurs in Eq. (1) when the peak tensile stress is zero or compressive (a negative number), in which case the life in undefined. In these situations it is not possible to use the peak tensile stress, but it is doubtful whether such situations are of any practical significance.

---

*The elastic strainrange is the total strainrange less the inelastic strainrange.

Originally the mean stress was used in the formulation. This term avoided the difficulty of a negative-peak tensile stress.* However, experience showed that the peak tensile stress correlated the data better than or as well as the mean stress. Therefore, the mean-stress term was abandoned in favor of the peak tensile strength.

The variables for the time term are the total cyclic time (or cyclic period), a time term proposed by Ostergren[6,7] for the fatigue of stainless steel at elevated temperature, and the time term in Coffin's Frequency-Separation Model.[4,5]

The total cyclic time, τ_{tot}, is used when the fatigue life of a material is sensitive to the entire time spent in one cycle. This situation might occur from environmental attack.

The time term proposed by Ostergren for stainless steel, τ_{tc}, is used when the fatigue life is reduced by cyclic histories in which a longer time is spent in a tensile hold than in a compressive hold

$$\tau_{tc} = \begin{cases} \tau_o + \tau_t + \tau_c & \text{if } \tau_t > \tau_c \\ \tau_o & \text{if } \tau_t \le \tau_c \end{cases} \quad (2)$$

---

*The exponential of the mean stress times a constant, exp. [$c \times \sigma_m$], was used in order to handle negative mean stresses. The exponential was to the base ten. This same procedure could be used for the tensile stress.

where τ_o = time per cycle spent in cycling

τ_t = time per cycle spent in tensile hold

τ_c = time per cycle spent in compressive hold

The subscript tc refers to tensile creep and is used to indicate that the time term applies to materials whose life is reduced by tensile-creep strain. The use of the time term is not limited to this type of material. It may be used for any material whose life is reduced by tensile holds regardless of the failure mechanisms.

The time term used in the Frequency-Separation Model, τ_{fs}, is the product of two terms defined as

$$\tau_{fs} = \left(\tau_t\right)^d \left(\frac{\tau_c}{\tau_t}\right)^e \tag{3}$$

where τ_t is the tension-going time, τ_c is the compression-going time, and d and e are material constants. The tension-going time is defined as the time in the cycle when the *inelastic strain rate is positive.* The compression-going time is defined in the same manner, except that the inelastic strain rate is negative. When the inelastic strain rate is zero, which occurs for elastic unloading, the time spent is added to τ_t if the total strain rate is positive and to τ_c if the rate is negative. The use of τ_{fs} implies that the life is sensitive to both the tension- and compression-going times. This variable introduces one more constant into the predictive equation, which becomes

$$N_f = A \left(\frac{\Delta\epsilon}{\epsilon_f}\right)^b \left(\frac{\sigma}{\sigma_y}\right)^c \left(\tau_t\right)^d \left(\frac{\tau_c}{\tau_t}\right)^e$$

The author's experience in using the SST Model has shown that the total time or the tensile-creep time reproduced the data better than or as well as the frequency-separation term. The only time the frequency-separation term would be used is when the reported data do not contain the necessary information to permit use of the tensile-creep term.

It should be noted that no attempt has been made to differentiate between environmental attack and creep damage. The time term in the model is intended to take into account either environmental attack or creep damage or their interaction.

USE OF THE MODEL

In order to use the SST Model a strain, stress, and time term must be selected for the particular material at the particular temperature under investigation. These terms are chosen in the following manner:

(a) Use the inelastic strainrange if the inelastic strains are moderate or large; otherwise use the elastic strainrange; (b) Use the stress term only if mean stresses are present; and (c) Use the tensile-creep time if the failure mode is similar to creep rupture;* otherwise use the total time. A least-squares linear regression is then performed using Eq. (1) and the three terms selected above in order to determine the material constants. Having determined the constants, the scatter band between the predicted and the observed life is calculated. If the scatter band is less than or equal to two, then an acceptable choice of variables has been found.

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*Use the frequency-separation term if the reported data prevent the calculation of the tensile-creep term.

If this scatter band is greater than two, then another choice of variables may be sought or the original selection retained, depending upon the wish of the investigator. Another choice of variables would be made in the same manner as above, except that one of the conditions would be relaxed and the other two retained. That is, if the original choice of variables were *the elastic strainrange*, *tensile stress*, and tensile-creep time, then subsequent choices could be the inelastic strainrange, tensile stress and tensile-creep time; the elastic strainrange, tensile stress and total time; or some other variation.

DISCUSSION OF THE MODEL

The difference between the SST Model and other models similar to it--namely, models due to Coffin,[4,5] and Ostergren[6,7]--is its concept. The SST Model provides a framework from which a specific equation is selected for a type of material behavior, rather than one equation to which different *types of material behavior are required to conform.* It is this framework of a power-law relation involving only a stress, strain, and time term which is the distinctive feature of the SST Model. Different equations can be derived from it in order to predict the high-temperature LCF behavior of a specific material at a specific temperature.

Although the SST Model evolved from the Ostergren Model, it is the author's belief that it is not simply a modification of it. The Ostergren Model postulates that the basic measure of fatigue damage is the product of the inelastic strainrange and the peak tensile strength. This cross-product

term is fundamental to the model. The SST Model uses the peak tensile stress only when mean stresses are present and includes it as a term separate from the inelastic strainrange.

An objection to the SST Model is that it is simply a collection of many models, each model being one collection of variables. The SST Model would then be the common-sense procedure of selecting the best model. This objection misses the essence of the SST Model. The model states that the fatigue life at elevated temperature is a function of the strainrange, a stress (when mean stresses exist), and a time term. For any given material at any given temperature, the appropriate terms for the strainrange, stress, and time may be different, but all that is necessary to predict the life is the power-law equation composed of these three terms.

EVALUATION OF SST MODEL

Data generated by the Air Force Materials Laboratory (AFML) on advanced nickel-base superalloys and data available in the literature on other materials were used to evaluate the model. The materials and references for the test data are summarized in Table 1. In all cases a data set was composed of one heat of material tested at one temperature. Data from different heats of the same material or from tests at different temperatures were not combined. By removing heat-to-heat variations and temperature effects from the data base, it was hoped that the effect of the mechanical parameters on fatigue life could be determined more accurately. The AFML data are for thermo-mechanically processed, cast, and wrought

TABLE 1

DATA BASE

Material	Temperature °F	Temperature °C	Reference
René 95	1200	650	11
AISI 304 Stainless Steel	1200	650	15
Incoloy 800	1200	650	15,16,17
2 1/4-Cr-1-Mo Steel	1100	593	18
2024-T4 Aluminum	72	22	12,19

René 95 at 1200°F (650°C).[11] The data were divided into two sections--baseline tests from which the constants in the model were found and verification tests which were predicted using these constants. Three materials considered for nuclear-power-plant applications were used--AISI 304 stainless steel (SS) at 1200°F (650°C),[15] Incoloy 800 at 1200°F (650°C),[15,16,17] and 2 1/4-Cr-1-Mo steel at 1100°F (593°C).[18] Fatigue data for 2024-T4 aluminum at room temperature in which large mean stresses were present[12,19] were used to evaluate the model for its ability to predict mean stress effects in the absence of creep or environmental attack.

The results of fitting the SST Model to the various data sets are summarized in Table 2 in which the variables, scatter band, and standard deviation are given. In all cases the data were correlated to within a scatter band of 2.1. The René 95 verification tests were predicted to within a scatter band of 2.6. Plots of the predicted and experimental lives for each material are shown in Figs. 1-6. A discussion on reading these plots is contained in the Appendix.

Generally, the initial choice of variables was used to predict the data, although some exceptions occurred. When the inelastic strains were large, the inelastic strainrange was used; when these strains were small, the elastic strainrange was used. Data containing mean stresses generally could not be predicted effectively unless the tensile-stress term was used. For the time term, the total time was used for the René 95 and the 2 1/4-Cr-1-Mo steel. The tensile-creep time was used for the AISI 304 SS and the Inco 800.

TABLE 2

RESULTS FOR THE SST MODEL

Material		Scatter Band	Standard Deviation	Strain	Stress	Time	A	b	c	d	ϵ_f in/in	σ_y ksi
René 95 1200°F (650°C)	Baseline Tests	2.1	0.10	Inelastic	Tensile	Total	28.1 (1)	-0.598	-3.31	-0.170	0.11	175
	Verification Tests	2.6	0.20	predicted using equation from baseline tests								
AISI 304 SS 1200°F (650°C)		2.0	0.12	Inelastic	---	Tensile Creep	4.30	-1.35	--	-0.212	0.47	22
Inco 800 1200°F (650°C)		1.6	0.10	Inelastic	---	Tensile Creep	1.92	-1.24	—	-0.269	0.88	13.5
2-1/4-Cr-1-Mo 1100°F (593°C)		1.4	0.07	Inelastic (2)	---	Total	2.70 (3)	-1.28	—	-0.0695	—	—
2024-T4 Room Temperature		1.9	0.13	Elastic	Tensile	---	1.51	-2.44	-2.53	---	0.43	44

(1) Units for the time are minutes.

(2) All combinations with inelastic strain, including inelastic strain alone, resulted in a scatter band of less than two.

(3) $\Delta\epsilon$ was not normalized.

The René 95 baseline data were correlated to within a scatter band of 2.1, and the predictions are shown in Fig. 1. The variables used to predict the René 95 data were the inelastic strainrange, the tensile stress, and the total time. The inelastic strainrange was surprising because the elastic strains of the data were much larger than the inelastic strains. The use of the elastic strainrange with the tensile stress and total time resulted in a scatter band of 2.5. It is not understood why the inelastic strainrange correlated the data better than the elastic strainrange. No segregation of the data was observed.*

The René 95 verification tests were predicted to within a scatter band of 2.6 using the equation determined from the baseline data. The predictions are shown in Fig. 2. The worst predicted tests were two slow-fast tests whose lives were much shorter than expected. However, the SST predictions for these tests were much better than those made by the four models previously evaluated for their ability to fit the René 95 data.[11]

The AISI 304 SS data were correlated to within a scatter band of 2.0 using the inelastic strainrange and tensile-creep time. A comparison of the predicted and actual lifetimes is shown in Fig. 3. No stress term was required because mean stresses were not present in the data. The one 10/3 and the two 30/3 tests† were under-predicted due to the tensile-creep time term not giving sufficient weight to the beneficial effect of the 3-min. compressive hold.

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*Segregation is defined as the consistent over- or under-prediction of a type of test and/or life-range.

†See Appendix for explanation of this notation.

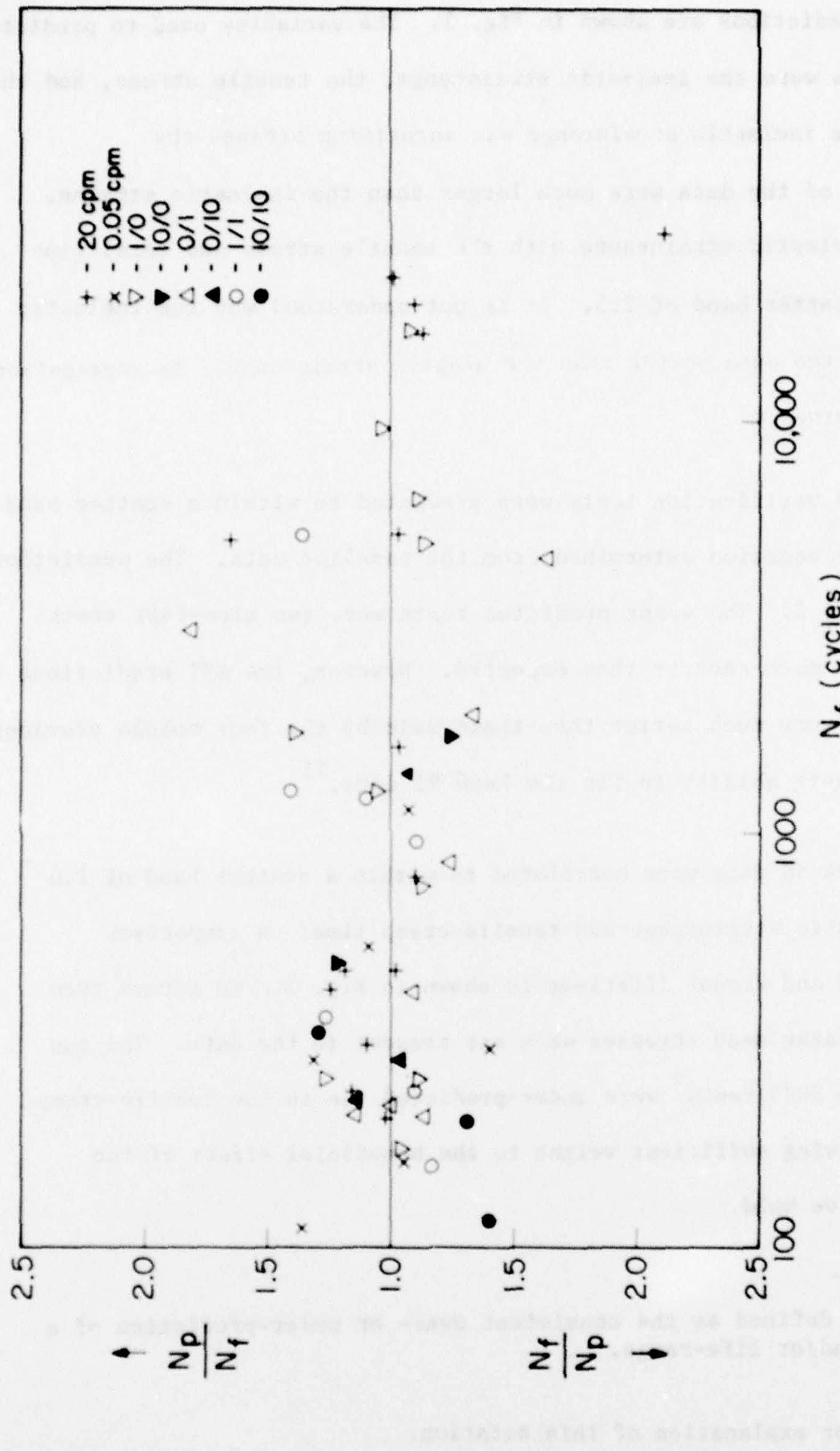

Figure 1. Predicted vs. Observed Life for Rene 95 Baseline Tests at 1200°F (650°C)

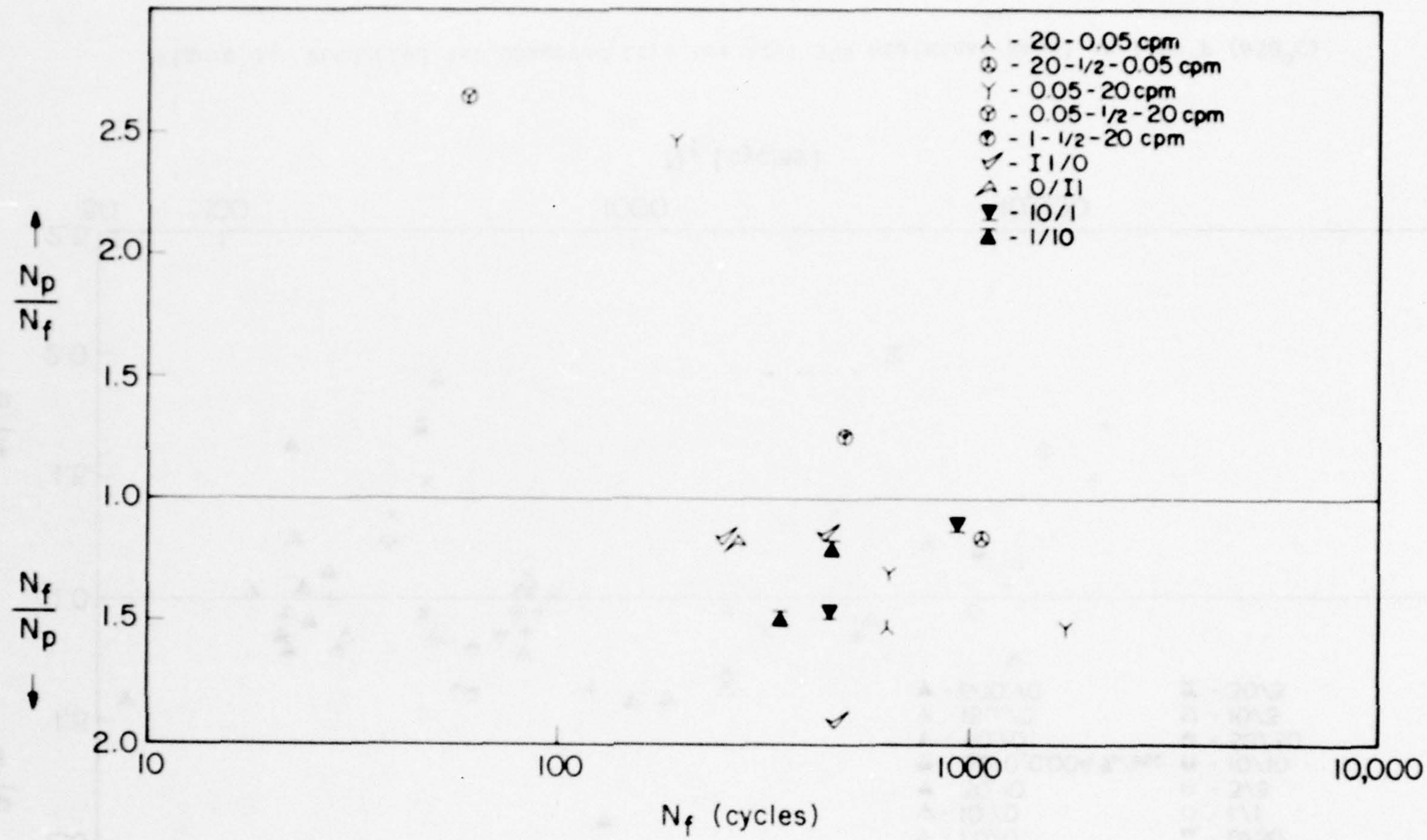

Figure 2. Predicted vs. Observed Life for René 95 Verification Tests at 1200°F (650°C)

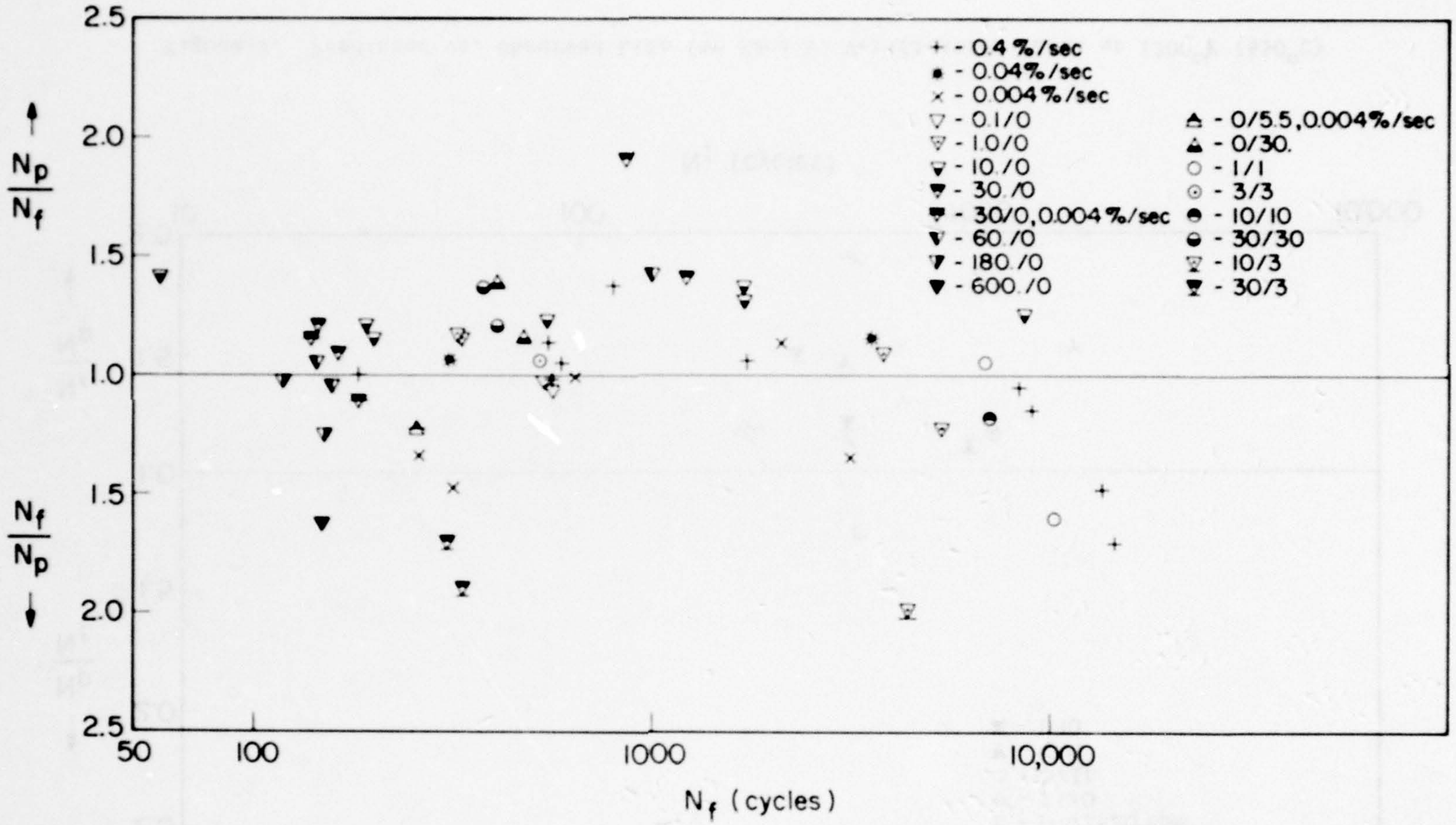

Figure 3. Predicted vs. Observed Life for AISI 304 Stainless Steel at 1200°F (650°C)

The Incoloy 800 data were correlated to within a scatter band of 1.6 and are shown in Fig. 4. The variables employed were the inelastic strainrange and the tensile-creep time. No stress term was used because no mean stresses existed. All of the 0.04%/sec strain-rate tests were underpredicted, but these predictions were within two-thirds of the actual failure life and improved for longer lives.

The 2 1/4-Cr-1-Mo steel data were correlated to within a scatter band of 1.4 using the inelastic strainrange and the total time.* The predictions are shown in Fig. 5. There was no segregation of the data. All of the expressions of the SST Model which are possible using inelastic strainrange as a variable yielded a scatter band of less than two. Although the total time is raised to a small power, 0.07, its use with the inelastic strainrange yielded the best results when scatter band, segregation, and fatigue mechanisms were considered.

The 2024-T4 aluminum data contained large mean stresses and strains. Since the tests were performed at room temperature, no time term was used in the model. This data set was used to examine the model's ability to predict mean stress effects.† Using the total strainrange and the tensile stress, the model was able to correlate these data to within a factor of 2.1. The predictions are shown in Fig. 6. The tests having compressive mean stresses

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*One long-life test on 2 1/4-Cr-1-Mo was not used in the data base because it was inconsistent with the remainder of the data base. This test, No. FB2-42, had a life of 227,000 cycles for an inelastic strainrange of 0.12%, whereas a similar test having an inelastic strainrange of 0.13% had a life of only 15,000 cycles.

†Although mean strain may be an important variable in these tests, it was not evaluated.

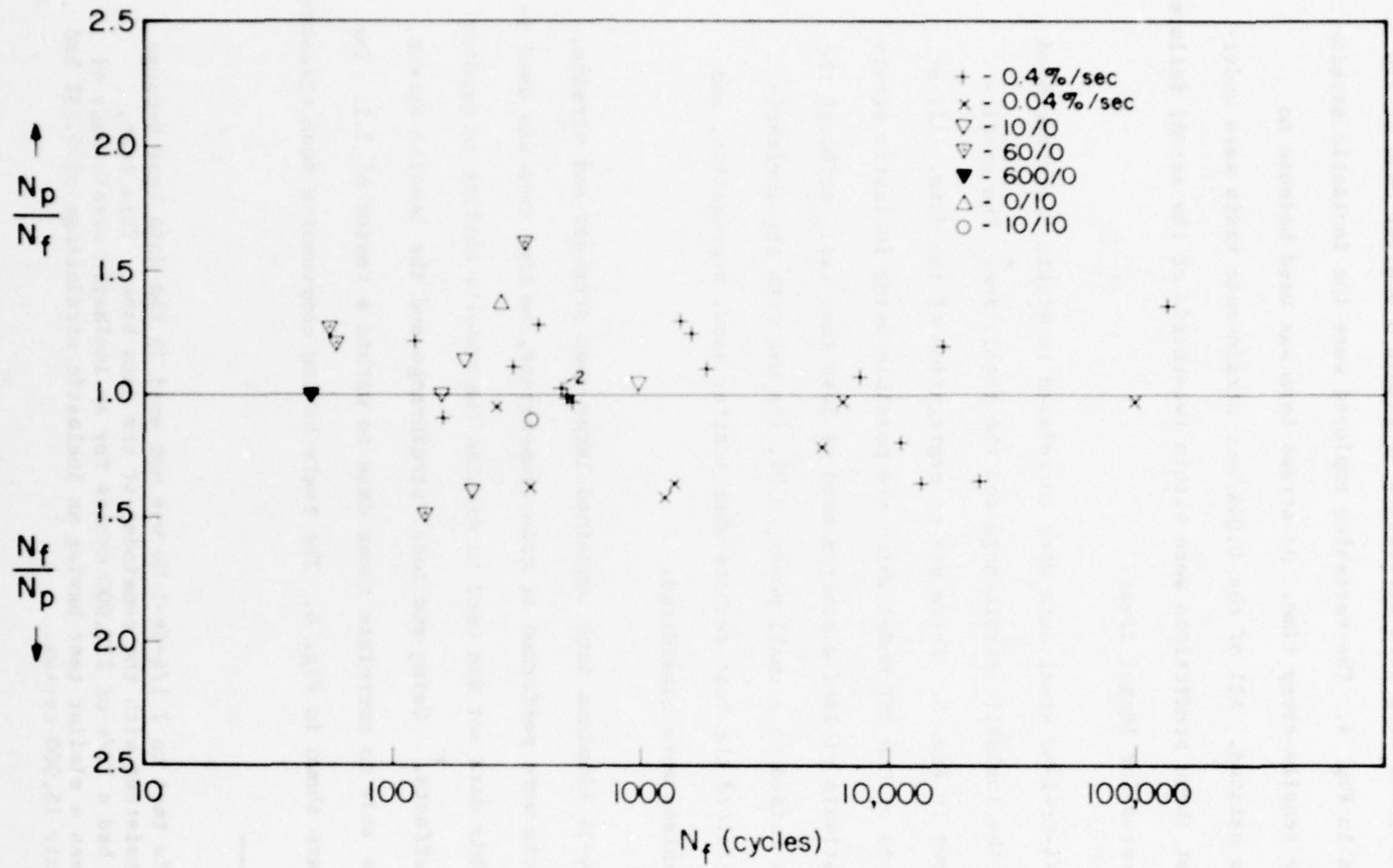

Figure 4. Predicted vs. Observed Life for Incoloy 800 at 1200°F (650°C)

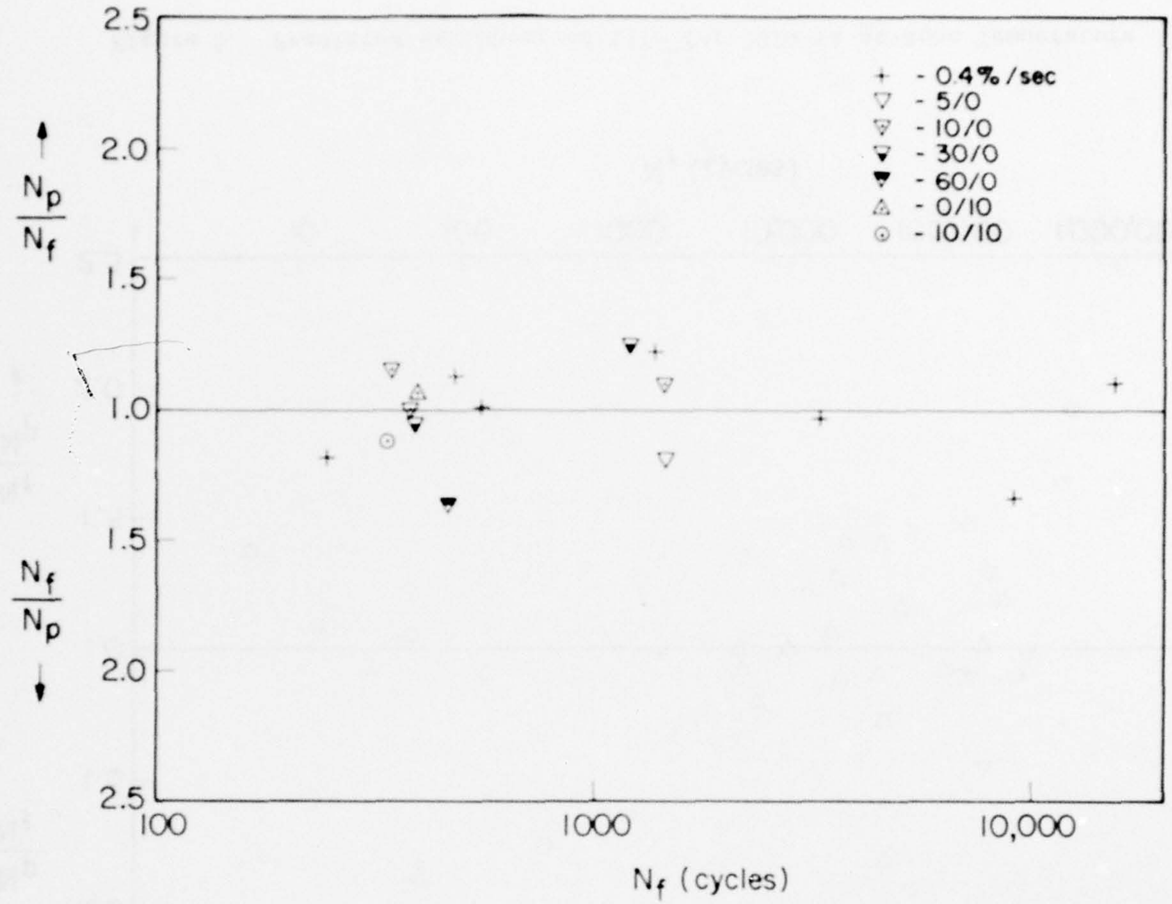

Figure 5. Predicted vs. Observed Life for 2 1/4-Cr-1-Mo Steel at 1100°F (593°C)

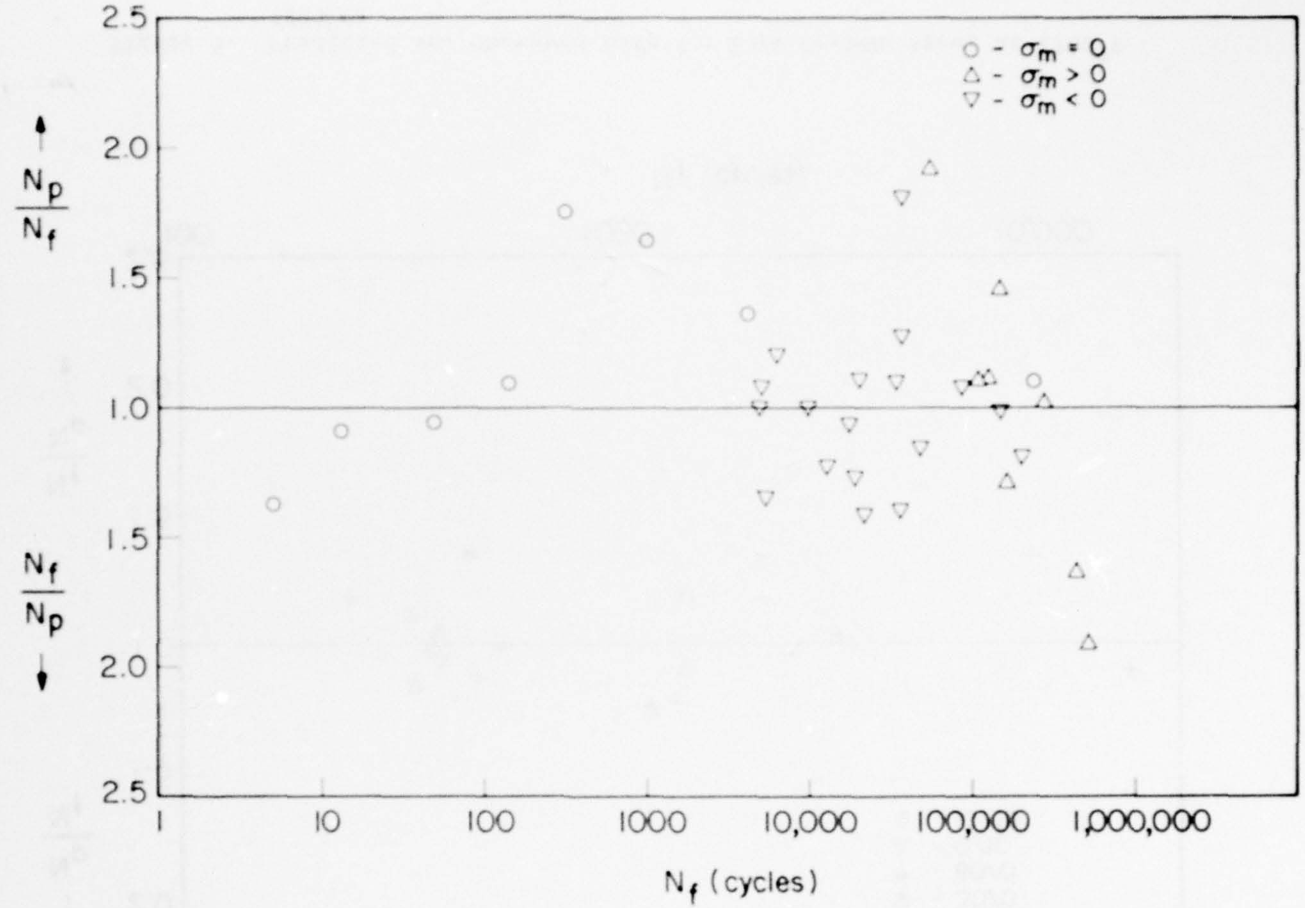

Figure 6. Predicted vs. Observed Life for 2024-T4 at Room Temperature

did not appear to be well predicted. Those tests having shorter lives were over-predicted while those having longer lives were under-predicted. This trend is troublesome and not understood.

CONCLUSIONS

The SST Model was able to correlate the data for five different materials to within a scatter band of 2.1 and to predict data to within a scatter band of 2.6. For the most part, the predictions were accurate, and little segregation of the data occurred. The variables used in the model generally were physically reasonable. It is hoped that the model can be applied to the correlation and prediction of more data in the literature, as well as to the resolution of some of the problems within the present data. Considering the present state of high-temperature LCF models, the SST Model appears to be both a viable and useful model worthy of consideration.

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APPENDIX

READING THE GRAPHS

The graph of the predicted and observed lives has been made in an unconventional manner in order to achieve a more meaningful display of the data. The observed life is plotted logarithmically on the horizontal axis. The ratio of the predicted life to the observed life or its inverse is plotted linearly on the vertical axis. When a perfect prediction is made, this ratio has the value of one. When the life is overpredicted, then the ratio of predicted to observed life is greater than one and is plotted above the perfect-fit line of one. When the life is underpredicted, then the ratio of observed to predicted life is greater than one and is plotted below the perfect fit-line. Thus, unconservative predictions are above the perfect fit line and conservative predictions are below it.

The notation for the types of tests that the symbols represent is defined as follows:

<u>x</u> cpm	:	continuous cycling at a rate of x cycles per min.
<u>x</u> - <u>y</u> cpm	:	continuous cycling at a tensile strain rate of <u>x</u> cpm and a compressive strain rate of <u>y</u> cpm.
<u>x</u> - ½ - <u>y</u> cpm	:	as in <u>x</u> - <u>y</u> cpm except that the change from the fast to the slow rate is made halfway between the peak and zero strain levels.
<u>x</u> %/sec	:	continuous cycling at a strain rate of <u>x</u> %/sec.
<u>x</u>/<u>y</u>	:	hold-time test in which x minutes is spent in a tensile hold and y minutes in a compressive hold. See the reference for the ramp rate.

I x/y	:	as in x/y except that the hold period occurs before the peak strain.
x/y, z strain rate	:	as in x/y except that the ramp portion is made at z %/sec strain rate.
$\sigma_m \left\{ \begin{matrix} = \\ > \\ < \end{matrix} \right\}$ 0:	:	the mean stress was equal to, greater than, or less than zero.

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